National Aeronautics and Space Administration

Analysis of Trim and Compressibility Effects in Extended Formation Flight

Mr. James Kless, Mr. Michael J. Aftosmis, and Dr. Marian Nemec

Aerospace Engineer
NASA Ames Research Center

2012 Technical Conference
NASA Fundamental Aeronautics Program
Subsonic Fixed Wing Project
Cleveland, OH, March 13-15, 2012

www.nasa.gov

Overview

- Extended formation flight
- Modeling approach
- Results
  - Mesh convergence study
  - Incompressible effects
    - Vortex position sensitivity
    - roll-trim
  - Compressible effects
    - roll-trim
- Summary
  - Current efforts

Background: Close Formations

14% reduction in heart rate when in formation (Welmerskirtch, et. al, 2001)

Background: Close Formations

Over 20% drag reduction and 18% fuel flow reduction for trailing aircraft (NASA, 2002)

Extended Formations

- ~15-40 span separation
- A safer approach to formation flight
- Can be implemented with today's aircrafts without modification
- Up to 10% fuel flow reduction for transport aircraft*

*Pahle, Joe, "A preliminary Investigation of Formation Flight for Drag Reduction on the C-17 aircraft"

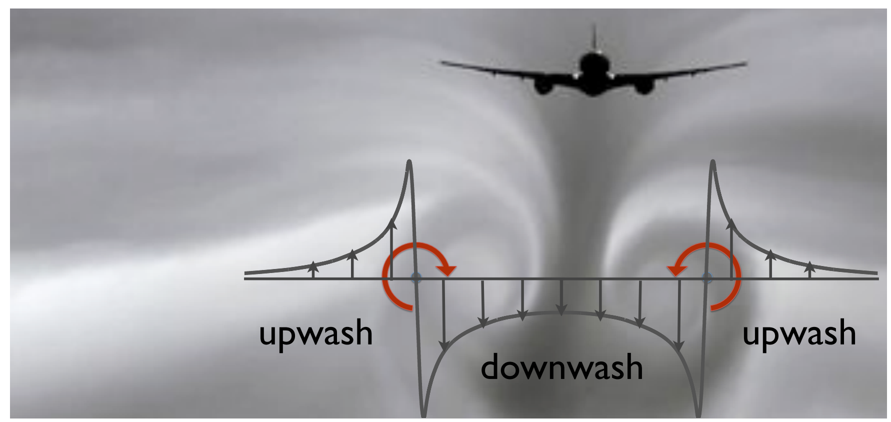
Extended Formations

- Provides a safer approach to formation flying, yet retains much of the fuel savings seen in close formation flight

Extended Formations

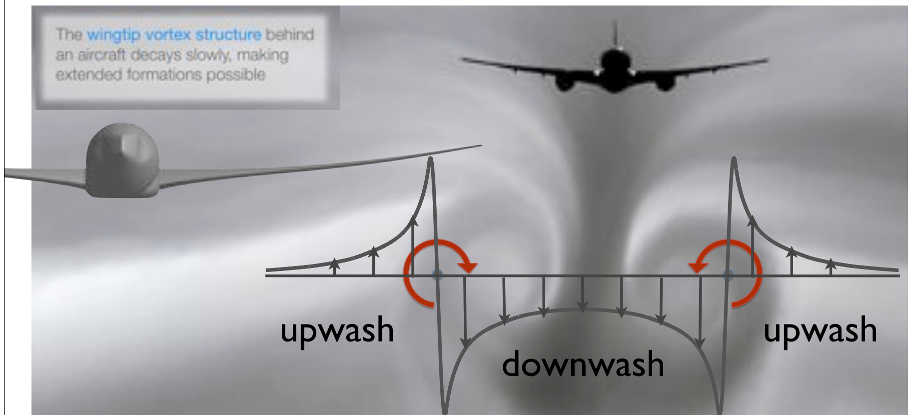
- Provides a safer approach to formation flying, yet retains much of the fuel savings seen in close formation flight

Extended Formations



- Provides a safer approach to formation flying, yet retains much of the fuel savings seen in close formation flight

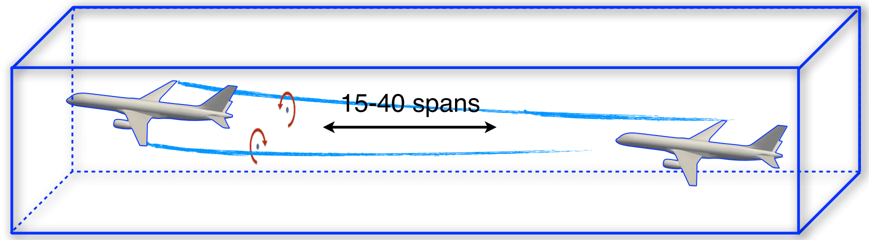
Extended Formations



- Provides a safer approach to formation flying, yet retains much of the fuel savings seen in close formation flight

Modeling

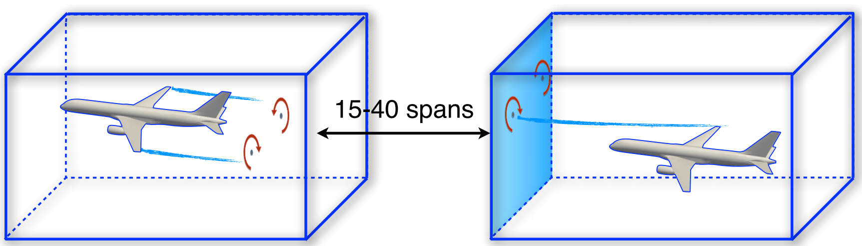
- In close formation, the trailing aircraft can influence the lead
- At 15-40 spans separation, this effect becomes negligible
- Extended formations decouple lead and follower aircraft



Lead Aircraft Trail Aircraft

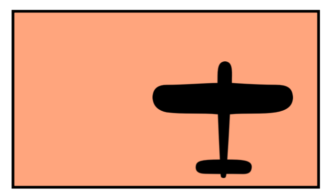
Modeling

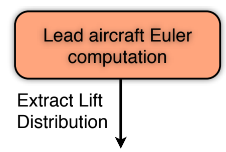
- In close formation, the trailing aircraft can influence the lead
- At 15-40 spans separation, this effect becomes negligible
- Extended formations decouple lead and follower aircraft



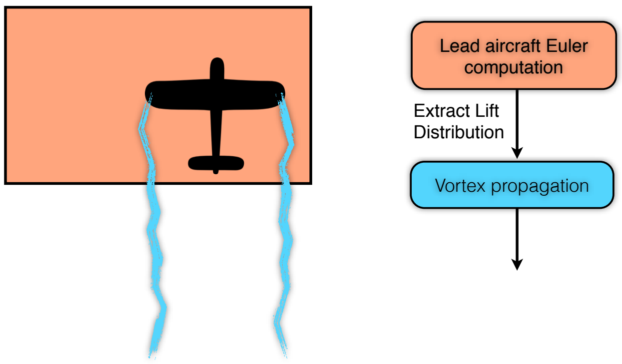
Lead Aircraft Trail Aircraft

Modeling Approach

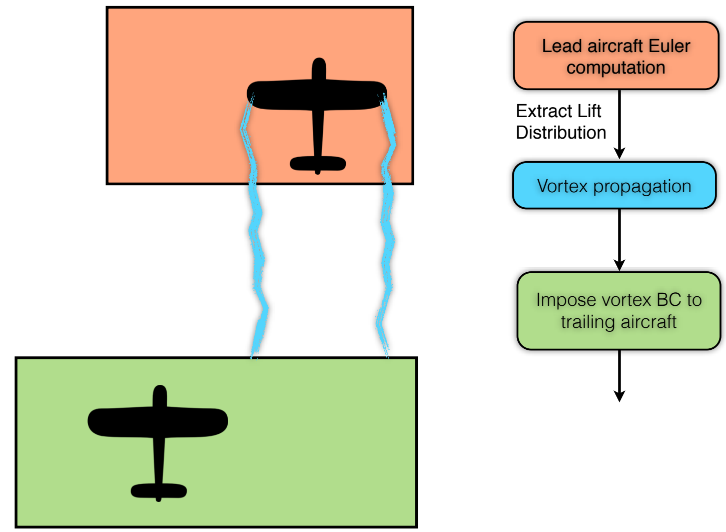




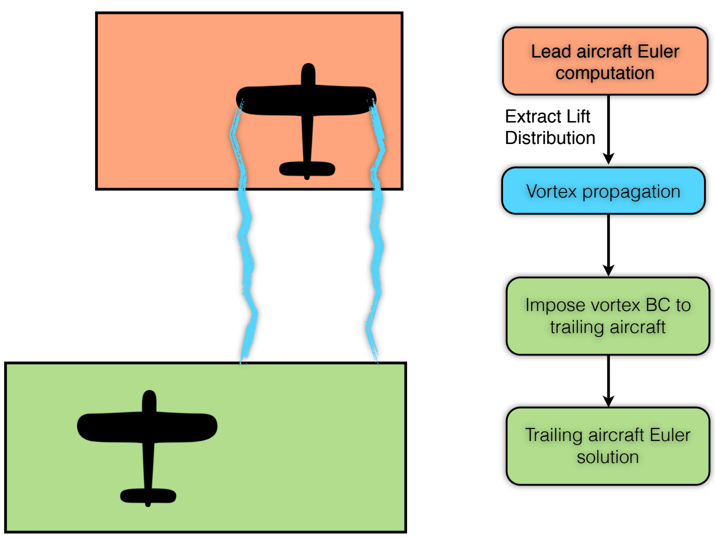
Modeling Approach



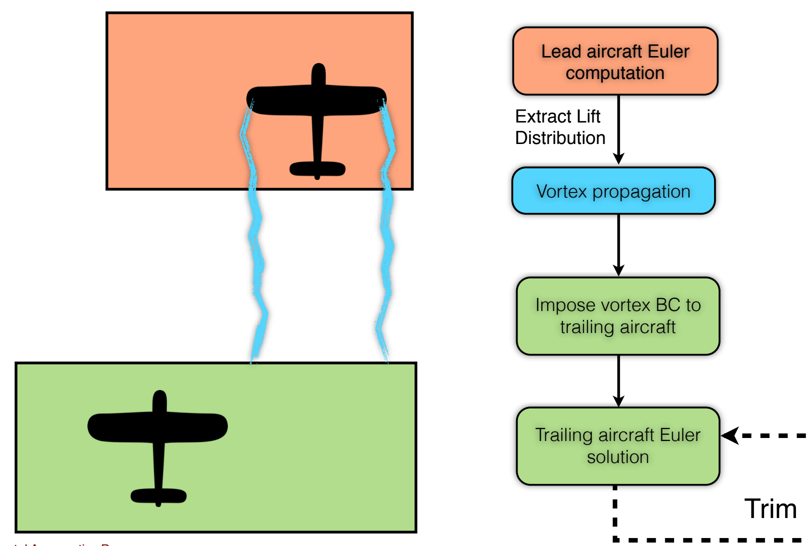
Modeling Approach



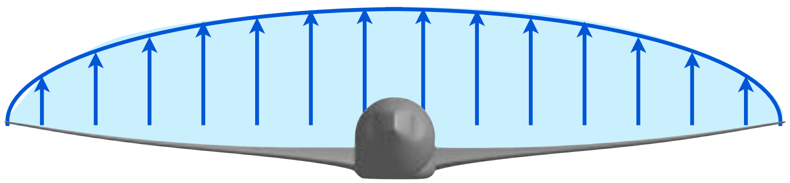
Modeling Approach



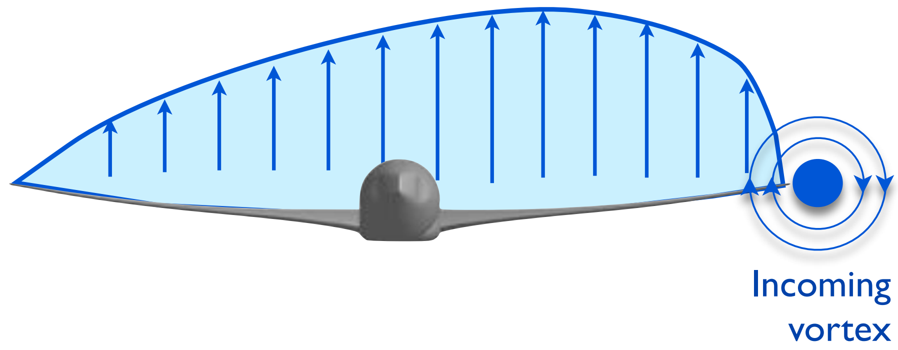
Modeling Approach



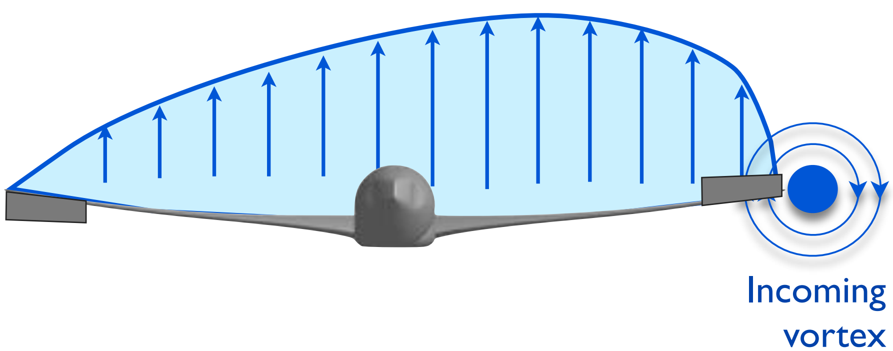
Out-of-Formation



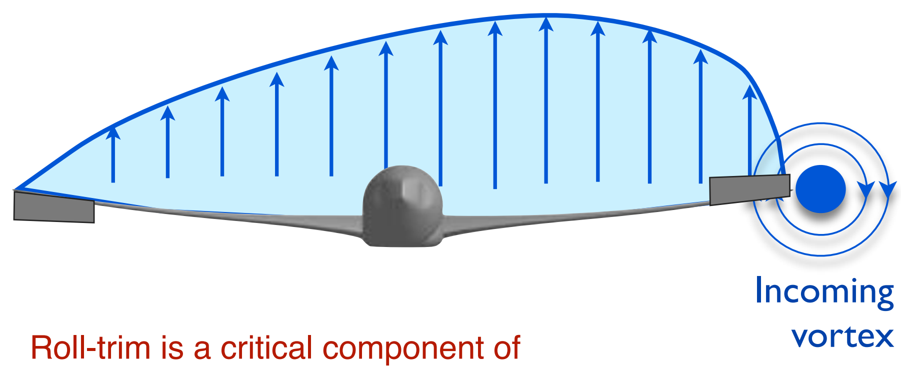
In-Formation



In-Formation



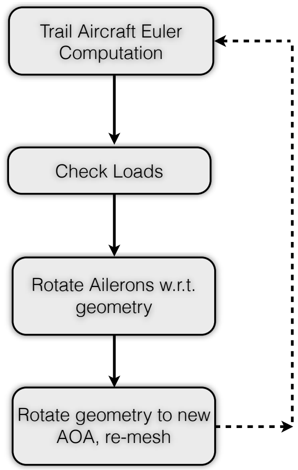
In-Formation



Roll-trim is a critical component of formation flying

Roll-Trim Strategy

- Algorithm for trim:
  - (1) Compute trail A/C flow solution
  - (2) Check Lift & Roll tolerance
  - (3) Deflect ailerons if necessary (roll)
  - (4) Adjust AOA if necessary (lift)

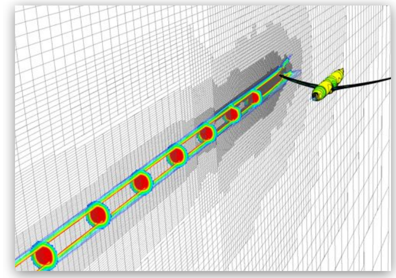


21

Flow Analysis: Cart3D

Requirements: automatic control surface deflections, geometry re-meshing, and high-fidelity CFD solutions

- Inviscid analysis package, 3D compressible Euler equations
- Unstructured Cartesian cells with cut-cells at wall
- Adjoint-Based Mesh Adaptation
- Highly automated for parameter sweeps, geometry manipulation, and re- meshing



22

Flow Analysis: Objective Functional

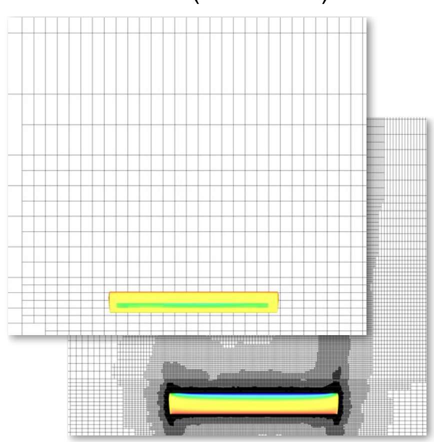
- Formation flight aims to improve induced drag at fixed lift...

$$C_{Di} = \frac{C_L^2}{\pi \, AR \, e}$$

- Span efficiency factor, e, is a natural choice

$$e = \frac{C_L^2}{\pi \, AR \, C_{Di}}$$

Initial Mesh (100k cells)



23

Flow Analysis: Objective Functional

- Formation flight aims to improve induced drag at fixed lift...

$$C_{Di} = \frac{C_L^2}{\pi \, AR \, e}$$

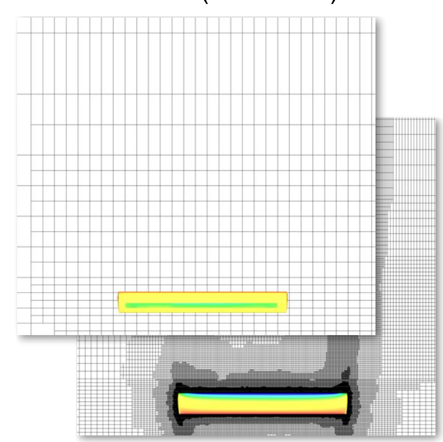
- Span efficiency factor, e, is a natural choice

$C_L \sim 0.5$

$$e = \frac{C_L^2}{\pi \, AR \, C_{Di}}$$

$C_D \sim 0.008$

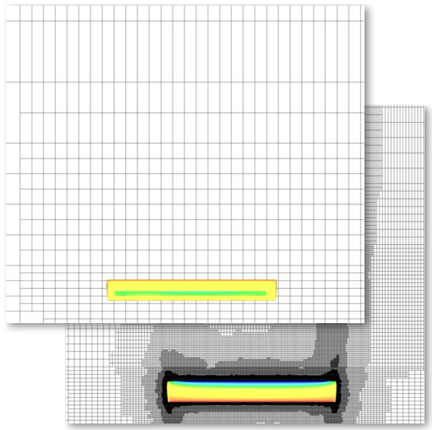
Initial Mesh (100k cells)



24

Flow Analysis: Objective Functional

Initial Mesh (100k cells)



- Formation flight aims to improve induced drag at fixed lift...

$$C_{Di} = \frac{C_L^2}{\pi\, AR\, e}$$

- Span efficiency factor, e, is a natural choice

$$e = \frac{C_L^2}{\pi\, AR\, C_{Di}}$$

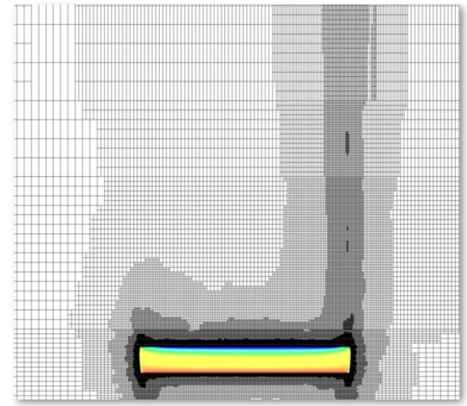
$C_L \sim 0.5$

$C_D \sim 0.008$

Expensive to converge due to drag sensitivity

Flow Analysis: Objective Functional

Final mesh (20 mil. cells)



- Formation flight aims to improve induced drag at fixed lift...

$$C_{Di} = \frac{C_L^2}{\pi\, AR\, e}$$

- Span efficiency factor, e, is a natural choice

$$e = \frac{C_L^2}{\pi\, AR\, C_{Di}}$$

$C_L \sim 0.5$

$C_D \sim 0.008$

Expensive to converge due to drag sensitivity

Results Outline

- Mesh convergence study
- Incompressible Effects
  - roll-trim
  - Vortex position sensitivity
- Compressible Effects
  - roll-trim

Formation flight metric

$$\text{drag fraction} = \frac{\sum D_{\text{in formation}}}{\sum D_{\text{out formation}}}$$

- Provides a measure for overall drag savings of the formation
- Focus on 2-aircraft echelon formations...

$$\text{drag fraction} = \frac{D_{\text{lead}} + D_{\text{trail}}}{2 D_{\text{lead}}}$$

Ex.: a drag fraction of 0.9 represents a 10% drag savings in formation flight

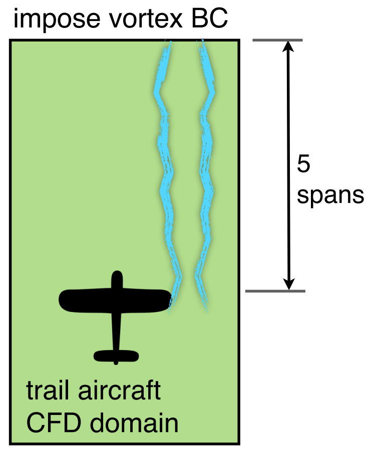
Results: Vortex in empty domain

Flow conditions

- Mach = 0.5
- CL (lead A/C) = 0.55
- Objective Function: Integrated pressure at 5 spans from inflow

Goal

- Verify mesh convergence of vortex in absence of geometry



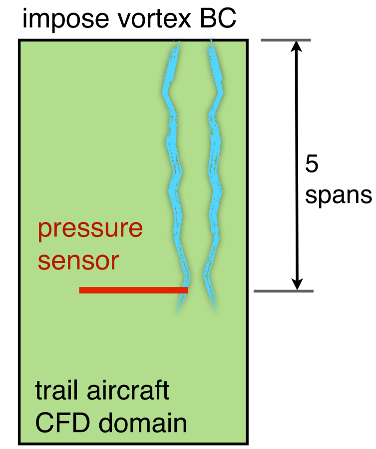
Results: Vortex in empty domain

Flow conditions

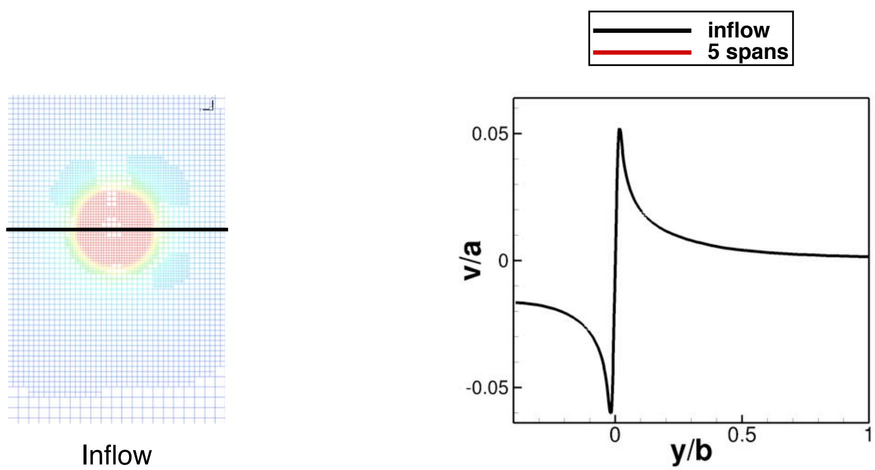
- Mach = 0.5
- CL (lead A/C) = 0.55
- Objective Function: Integrated pressure at 5 spans from inflow

Goal

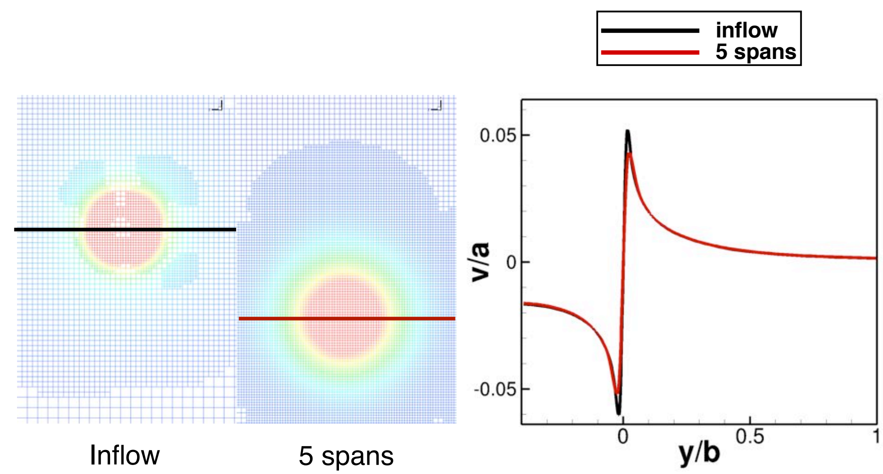
- Verify mesh convergence of vortex in absence of geometry



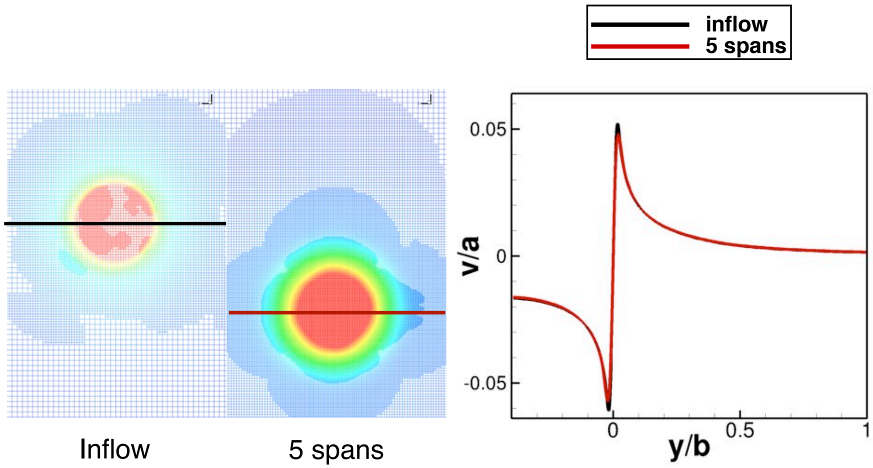
Results: Vortex in empty domain



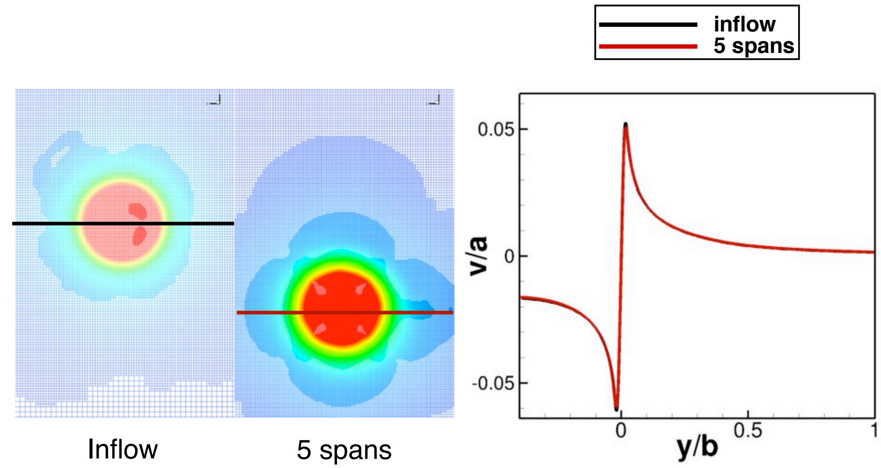
Results: Vortex in empty domain



Results: Vortex in empty domain



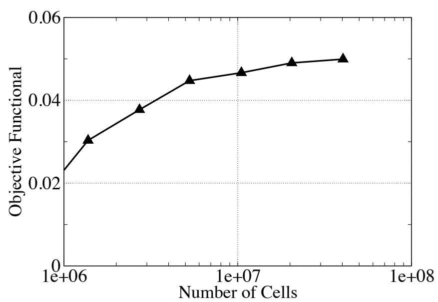
Results: Vortex in empty domain

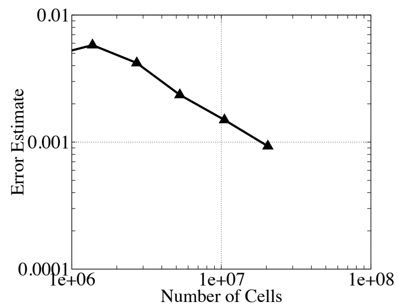


Results: Vortex in empty domain

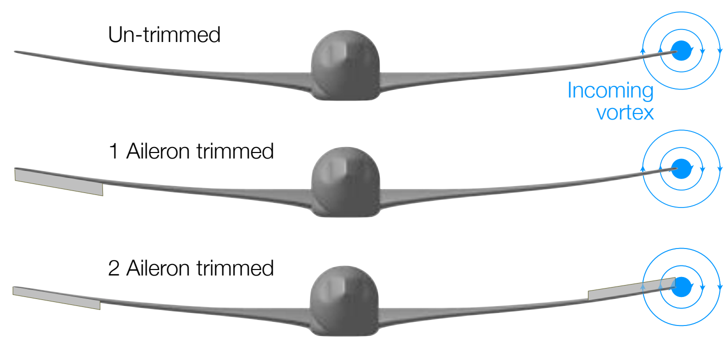
Mach = 0.5

- Objective functional: integrated pressure 5 spans downstream





Results: Trimming Configurations



- un-trimmed (baseline) configuration contains no ailerons
- 1-aileron deflected; increases lift on out-of-vortex wing
- 2-aileron deflected; trims in conventional manner

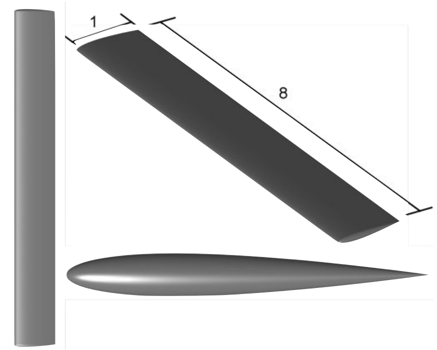
Results: Simple Wing

Geometry

- Sub-sonic straight wing w/ NACA 0012 sections

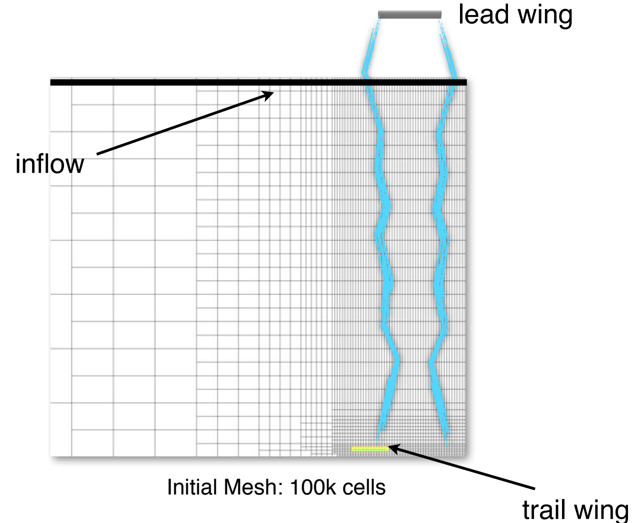
Goals

- Quantify/Verify incompressible formation flight drag savings
- Roll-trim effects
- Determine trail A/C position sensitivity



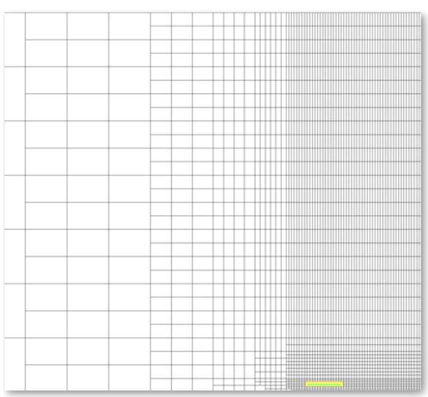
Geometry	C_L	M_∞	AR	$S_{ref}(ft^2)$
NACA 0012 Wing	0.55	0.5	8	8

Results: Simple Wing

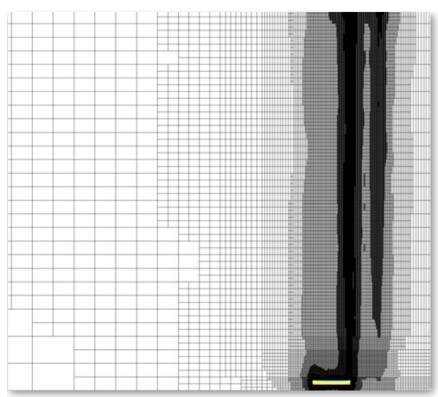


Initial Mesh: 100k cells

Results: Simple Wing

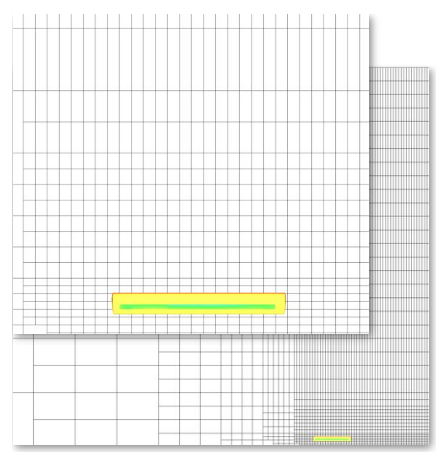


Initial Mesh: 100k cells

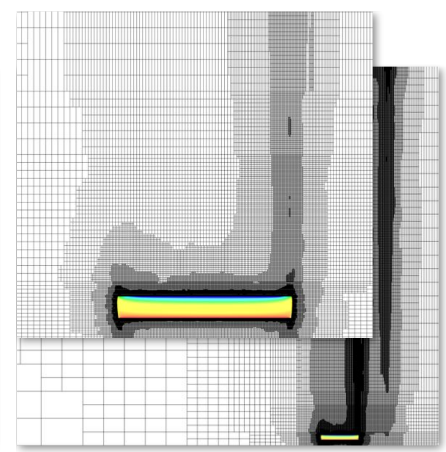


Final Mesh: 20 Mil. cells

Results: Simple Wing

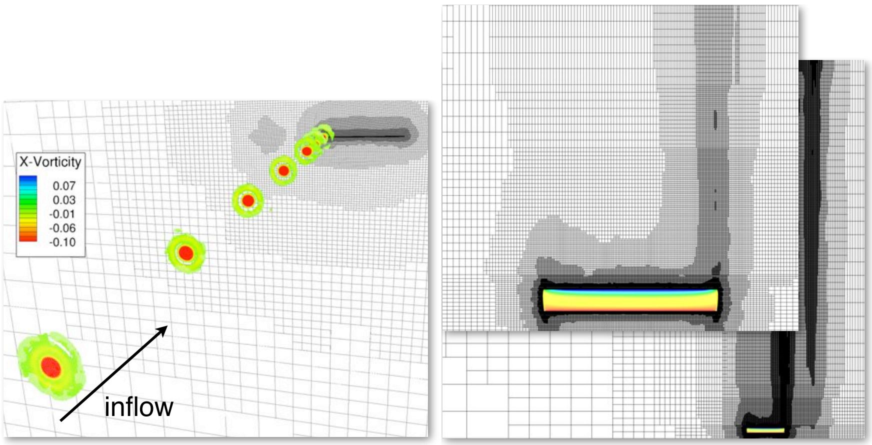


Initial Mesh: 100k cells



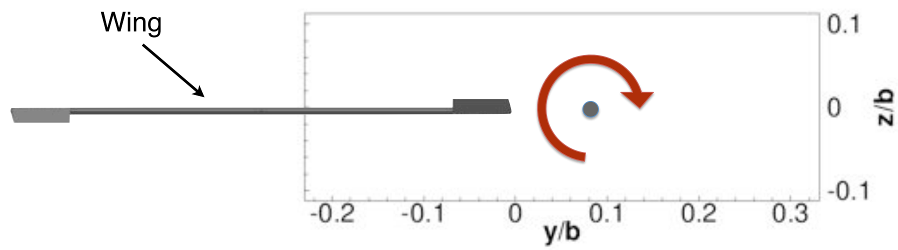
Final Mesh: 20 Mil. cells

Results: Simple Wing



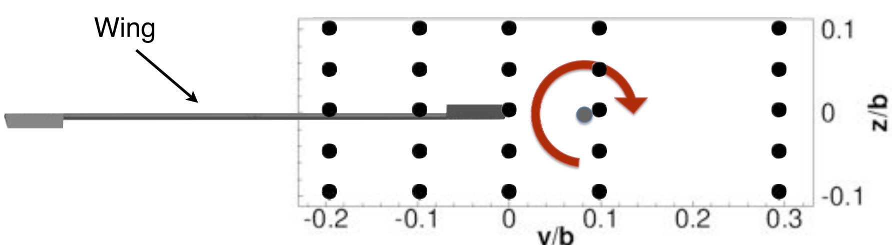
Final Mesh: 20 Mil. cells

Results: Vortex Position Sensitivity



*View behind wing facing upstream

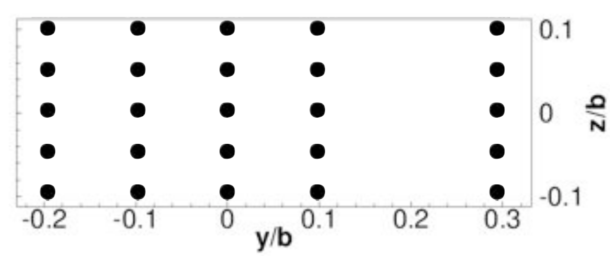
Results: Vortex Position Sensitivity



● CFD point

*View behind wing facing upstream

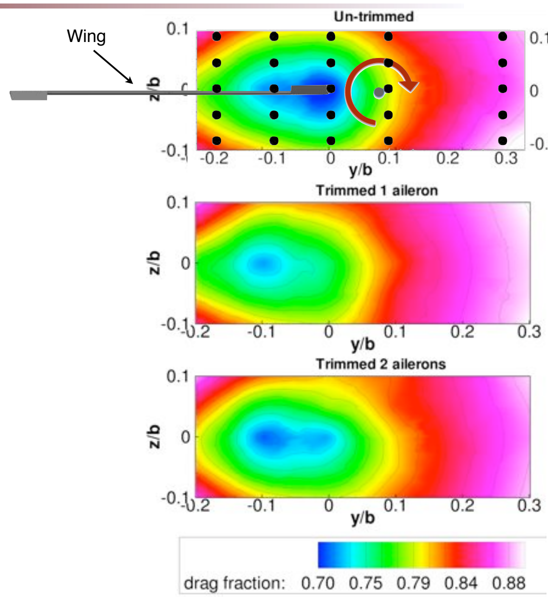
Results: Vortex Position Sensitivity



● CFD point

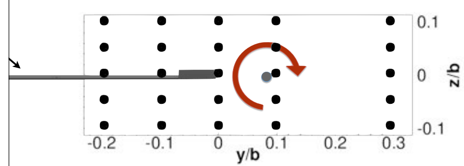
*View behind wing facing upstream

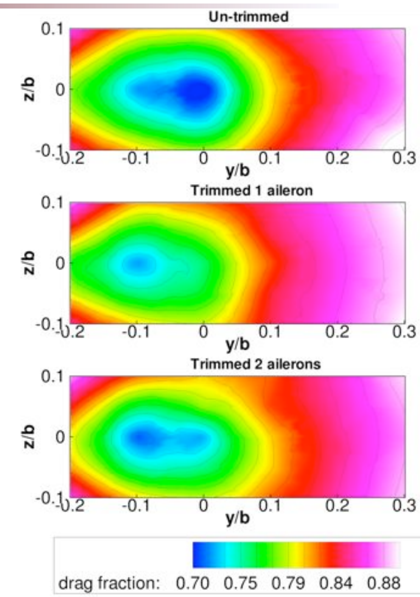
Results: Vortex Position Sensitivity



Results: Vortex Position Sensitivity

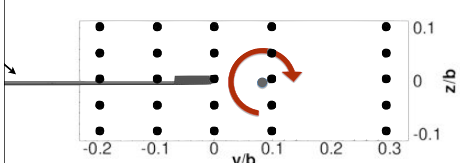
- Optimal vortex location migrates inboard w/ trim
- 2-aileron outperforms 1-aileron trim
- 3-5% decrease in drag fraction for 2-aileron

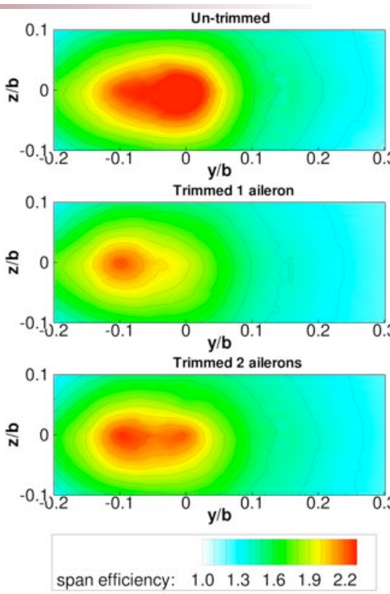




Results: Vortex Position Sensitivity

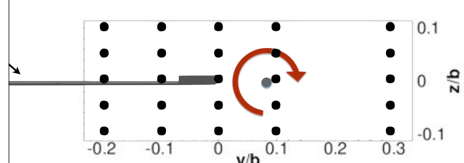
- un-trimmed, optimal span efficiency ~2.2 @ wingtip
- Optimal vortex location migrates inboard w/ trim
- 2-aileron trimmed outperforms 1-aileron

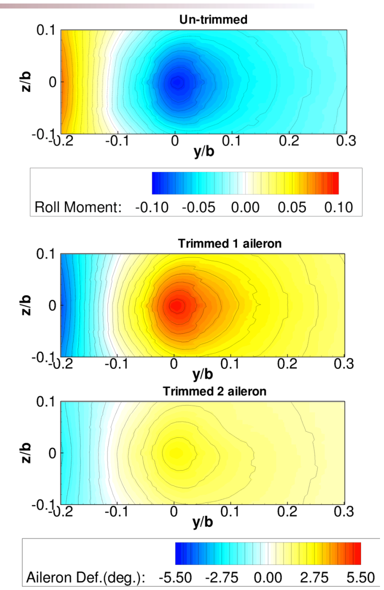




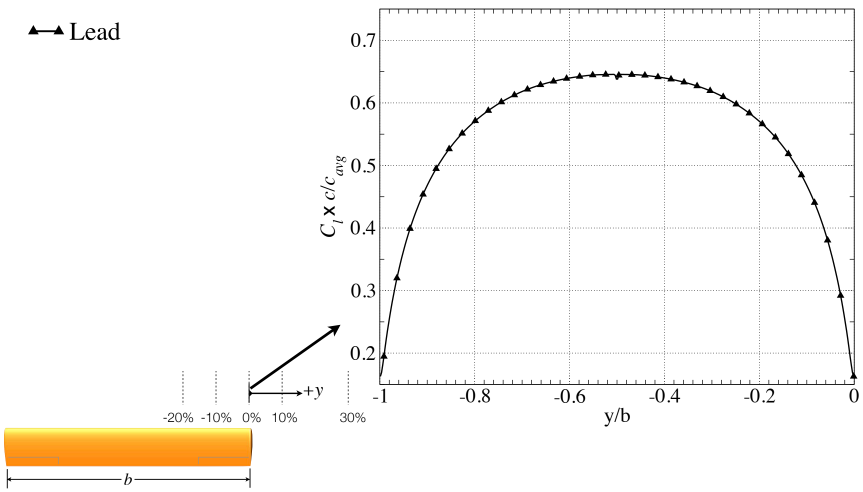
Results: Vortex Position Sensitivity

- Largest induced rolling moments occur at wingtip and 20% overlap
- Near 10% overlap, no induced rolling moments, yet close to optimal drag savings

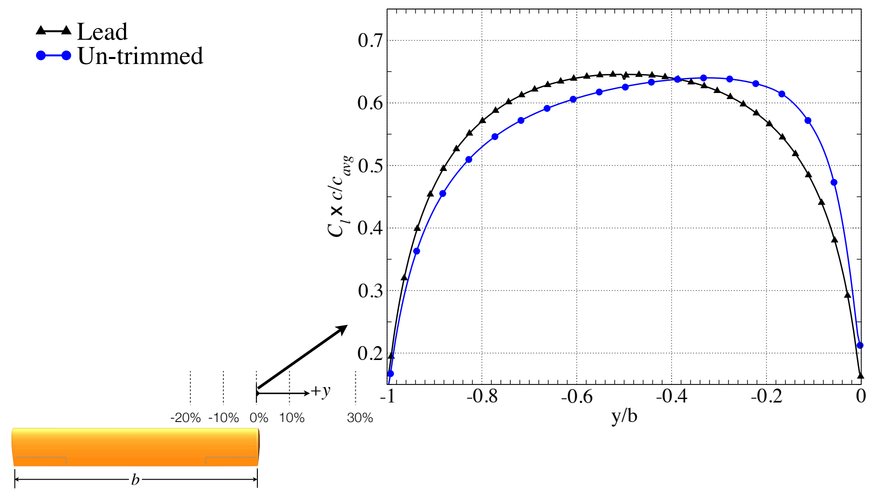




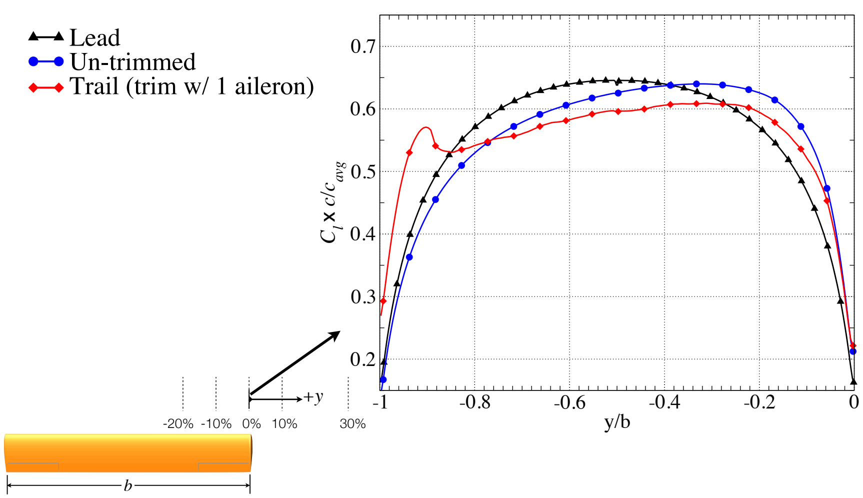
Results: Vortex Position Sensitivity



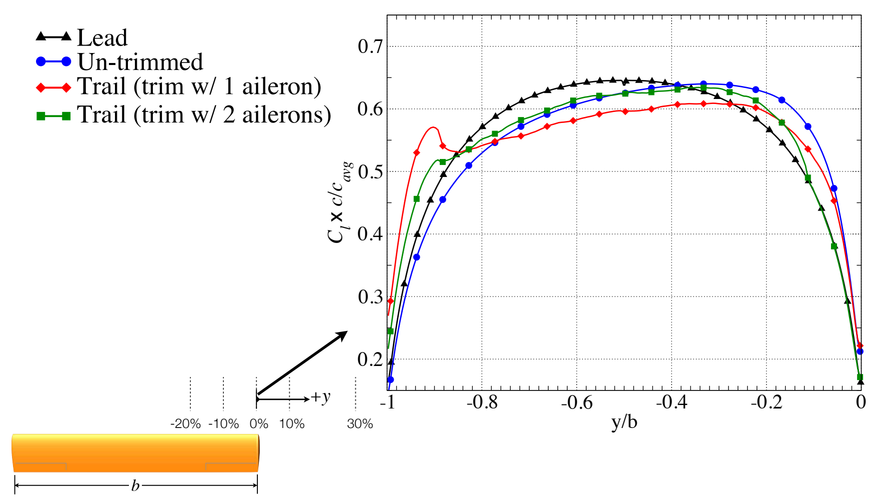
Results: Vortex Position Sensitivity



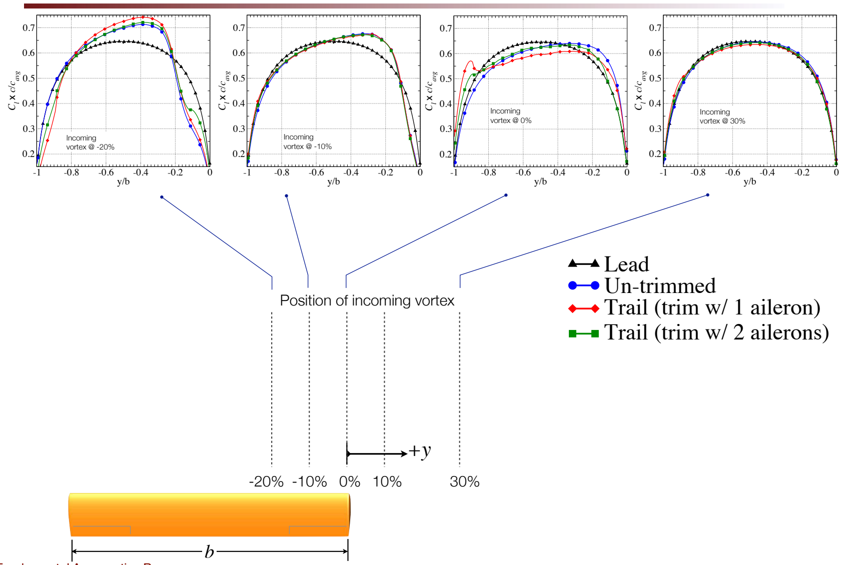
Results: Vortex Position Sensitivity



Results: Vortex Position Sensitivity



Results: Vortex Position Sensitivity



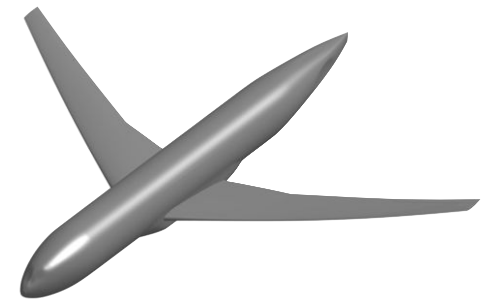
Results: Common Research Model

Geometry

- Modified CRM from 4th AIAA Drag Prediction Workshop*

Goals

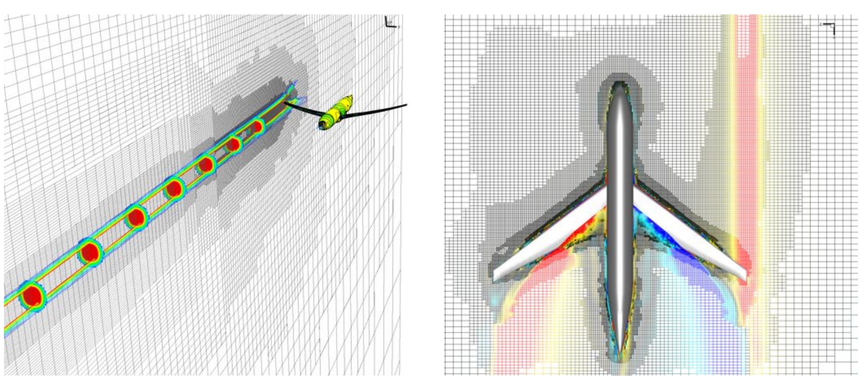
- Quantify compressible formation flight drag savings
- Determine roll-trim effects on more realistic wing/body geometry



Geometry	C_L	M_∞	AR	$S_{ref}(ft^2)$
CRM	0.5	0.83	9	4130

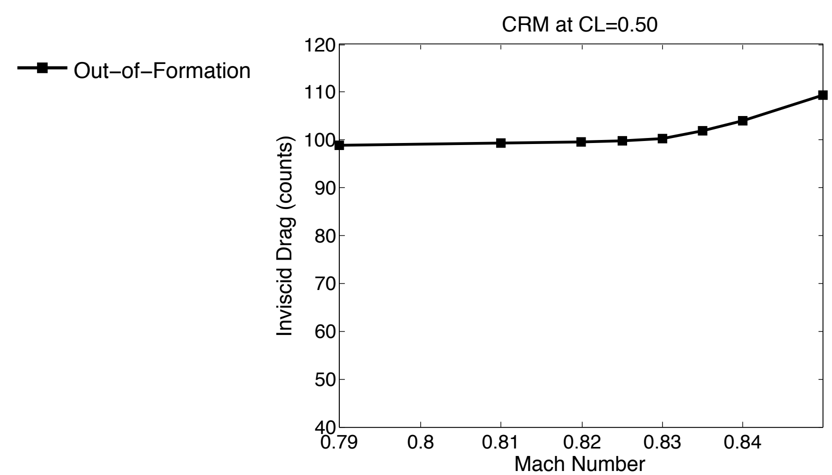
*Vassberg, J. C.,et al. Development of a Common Research Model for Applied CFD Validation Studies, AIAA Applied Aerodynamics Conference, AIAA 2008-6919, August 2008.

Results: CRM

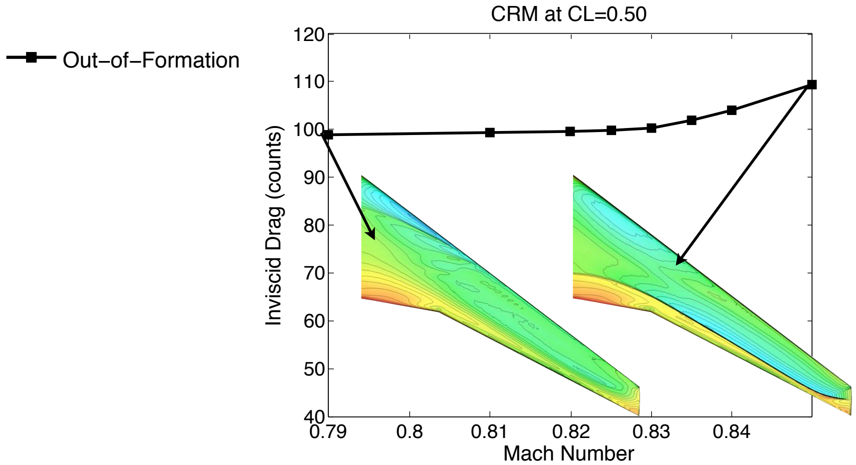


Final Mesh: 40 Mil. cells

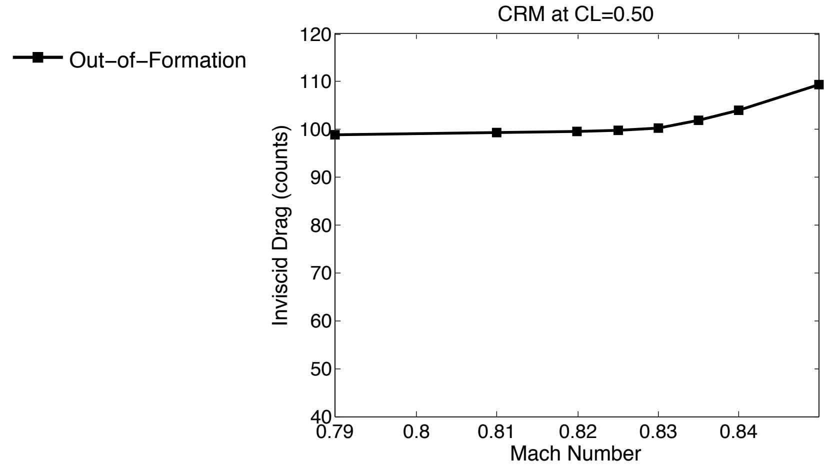
Results: CRM



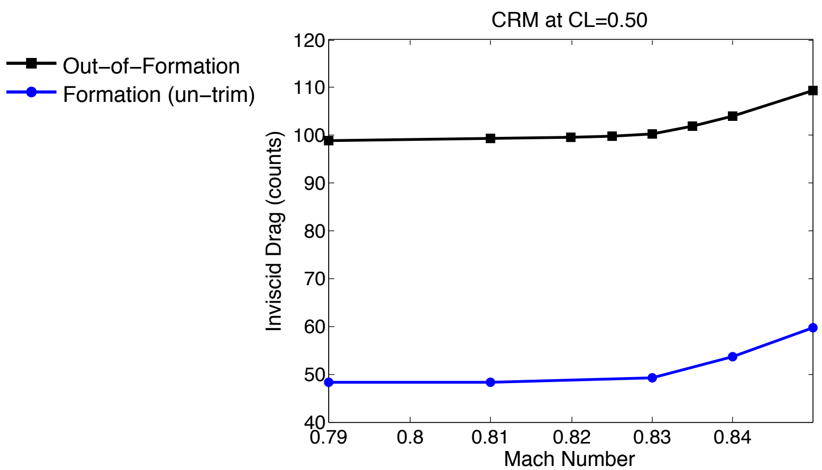
Results: CRM



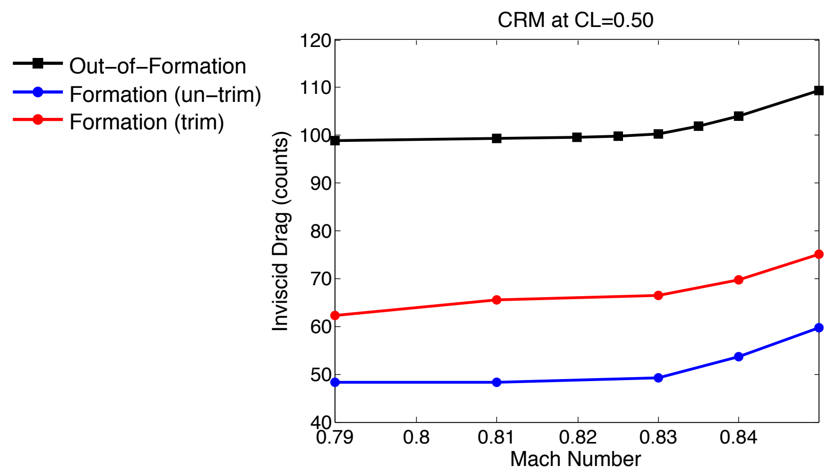
Results: CRM



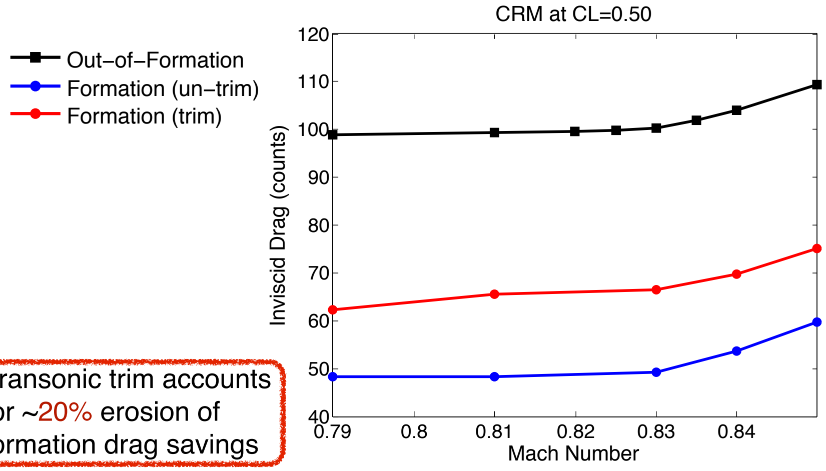
Results: CRM



Results: CRM

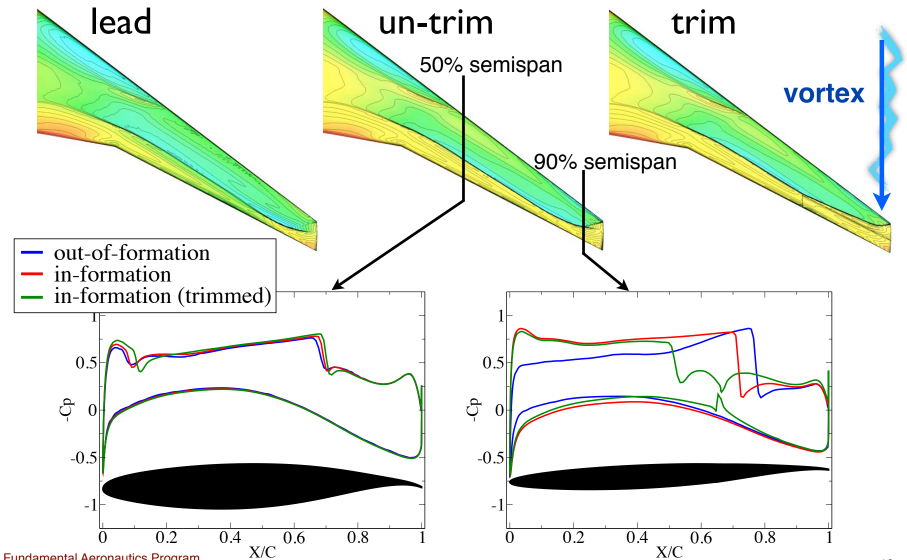


Results: CRM

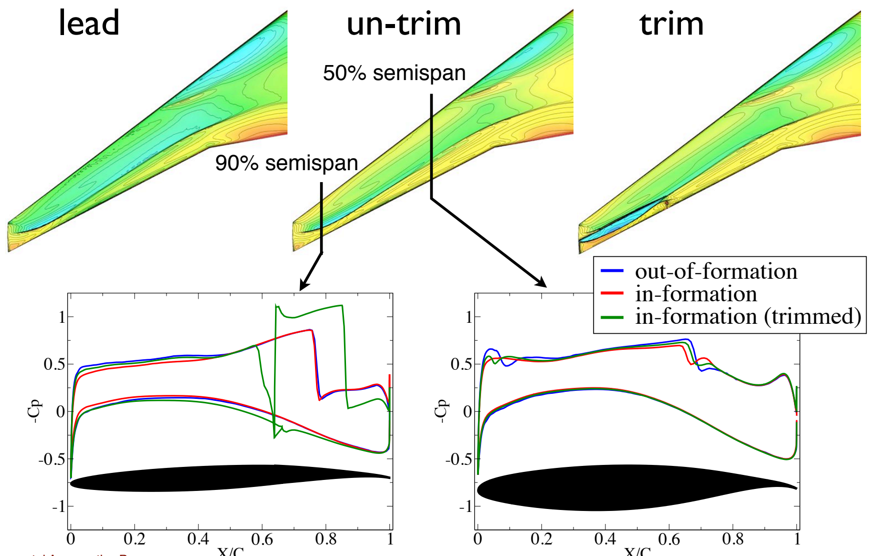


Transonic trim accounts for ~20% erosion of formation drag savings

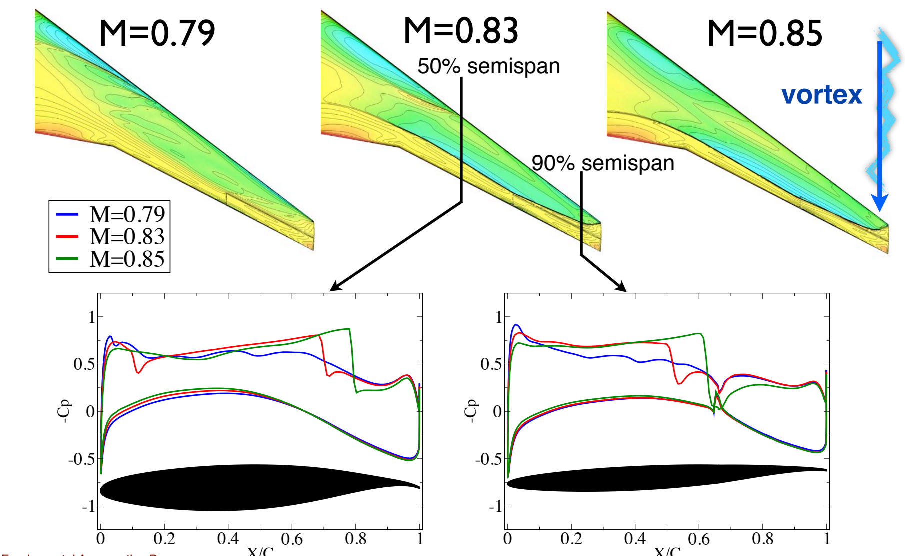
CRM, Mach = 0.83



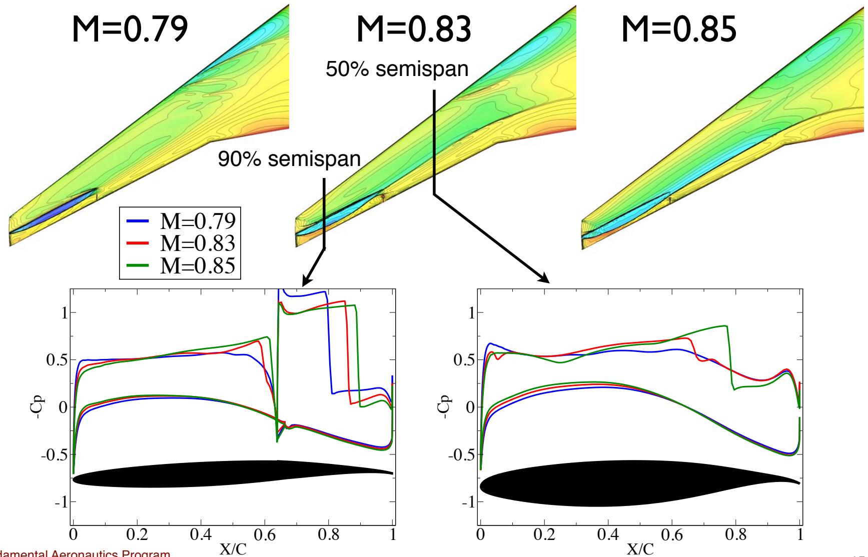
CRM, Mach = 0.83



CRM, In-Formation, trimmed



CRM, In-Formation, trimmed



Summary

- Performed relevant verification for vortex boundary condition
- Developed methodology for evaluating formation flight benefits for 2-aircraft echelon formations
- Developed quantitative benefit maps for trail aircraft positioning
- Evaluated erosion of formation flight benefits as a result of trim and compressibility

Open Issues

- Complete benefits map for summer conference
- Extend analysis to > 2 aircraft formations
- Effects of heterogenous aircrafts in formation
- Deliver analytic drag model for formation flight including trim/ compressibility for use in NAS models

Wake Propagation Model

*Augmented Betz Method**

- Far-field conservation method
- Experimental core-size data
- LES vortex decay rates

Assumptions

- Viscous effects neglected during rollup
- All vorticity from lead is axis-symmetrically rolled-up into 2 vortices

Governing Equations:

continuity:

$$\frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0$$

vorticity:

$$\frac{\partial \zeta}{\partial t} + u_y \frac{\partial \zeta}{\partial y} + u_z \frac{\partial \zeta}{\partial z} = \nu \left(\frac{\partial^2 \zeta}{\partial y^2} + \frac{\partial^2 \zeta}{\partial z^2} \right)$$

$$\left(\text{where } \zeta = \frac{\partial u_z}{\partial y} - \frac{\partial u_y}{\partial z} \right)$$

Time Invariants:

$$\Gamma_0 = \int \zeta dA$$

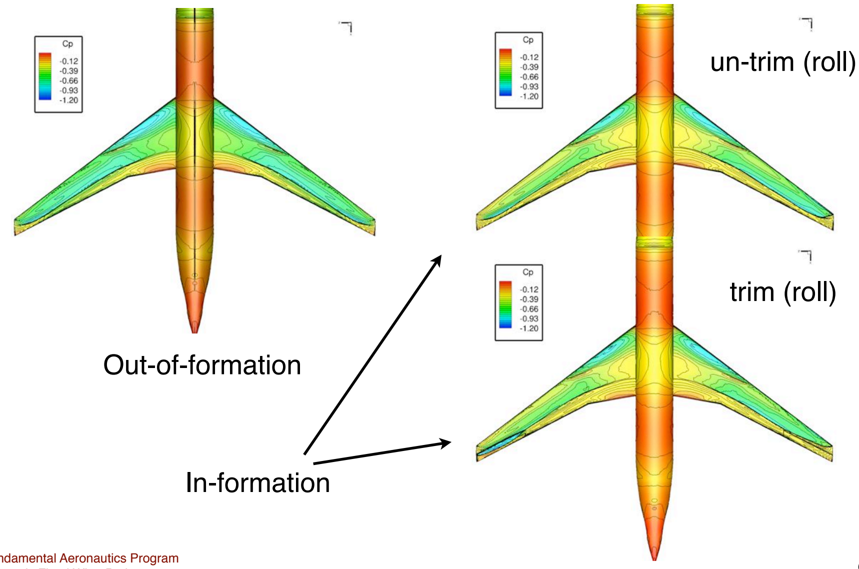
$$\Gamma_y = \int y \zeta dA$$

$$\Gamma_z = \int z \zeta dA$$

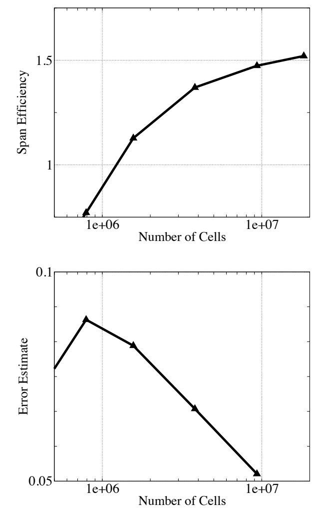
$$\Gamma_r = \int (y^2 + z^2) \zeta dA$$

*Ning, Andrew, Aerodynamic Performance of Extended Formation Flight, Journal of Aircraft, Vol. 48, No. 3, May-June 2011

Results: CRM at M=0.83



Results: Simple Wing



$$e = \frac{C_L^2}{\pi \, AR \, C_{Di}}$$